Velocity Distribution in a Room with Displacement Ventilation and Low-Level Diffusers

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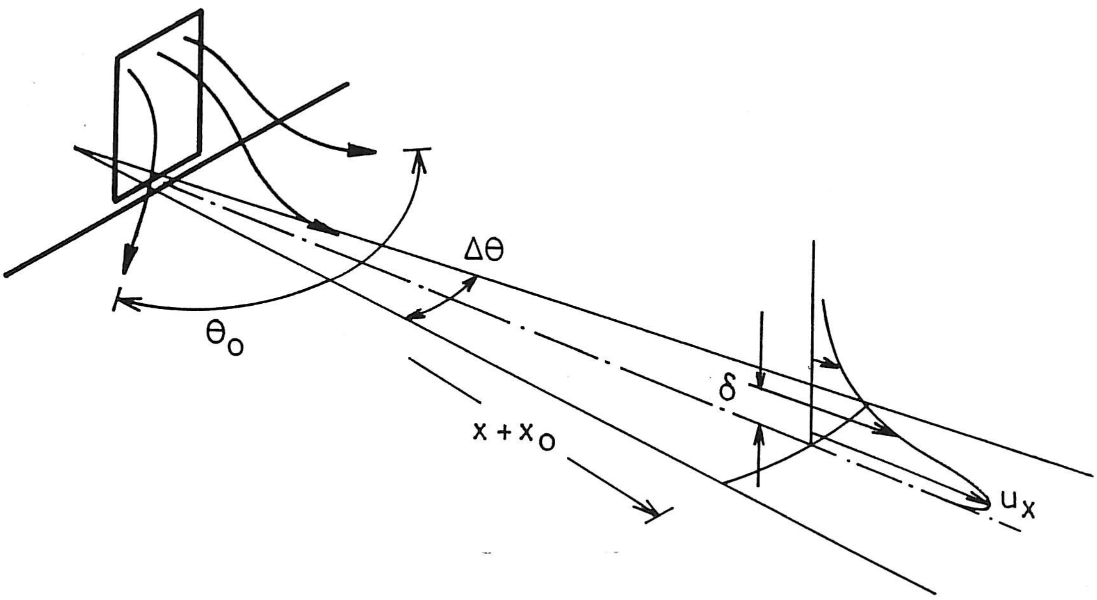

International Energy Agency, Energy Conservation in Buildings and Community Systems, Annex 20: Air Flow Pattern within Buildings

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SUMMARY

The article describes experiments with wall-mounted air terminal devices. The airflow from an air terminal device will influence the occupants' thermal comfort and it is therefore important to develop an expression for this flow. The velocity at the floor is influenced by the flow rate to the room, by the temperature difference and the type of diffuser. The flow is stratified at large temperature differences. The article shows the development of a semi-analytical expression for the velocity distribution in the vicinity of the floor. It is shown that openings between obstacles placed direct on the floor will generate a flow similar to the air movement in front of a diffuser. A semi-analytical equation for the velocity distribution is also given in the article.

International Energy Agency, Energy Conservation in Buildings and Community Systems, Annex 20: Air Flow Pattern within Buildings.

RESEARCH ITEM NO. 1.50

VELOCITY DISTRIBUTION IN A ROOM WITH DISPLACEMENT VENTILATION AND LOW-LEVEL DIFFUSERS

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INTRODUCTION

For many years ventilation systems with vertical displacement flow have been used in industrial areas with high thermal loads. Quite recently the displacement flow systems have grown popular as comfort ventilation in rooms with thermal loads as e.g. offices.

The air is supplied direct into the occupied zone at low velocity from wall-mounted diffusers. The plumes from hot surfaces, from equipment and from persons entrain air into the occupied zone and create a natural convection flow upwards in the room, see figure 1.

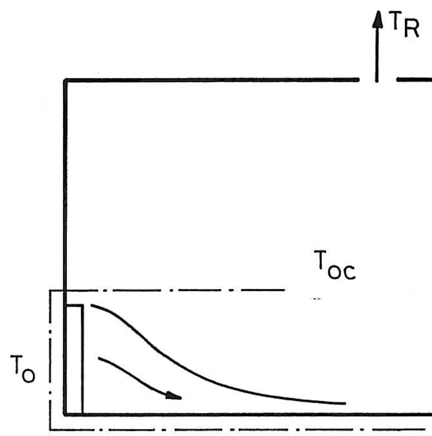

Figure 1. Room with low-level diffuser, heat source and displacement flow.

The displacement flow systems have two advantages compared with traditional mixing systems.

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- They are energy efficient. It is possible to remove exhaust air from the room where the temperature is several degrees above the temperature in the occupied zone which allows a higher air inlet temperature at the same load.

- They can have an appropriate distribution of contaminated air. The vertical temperature gradient (or stratification) implies that fresh air and contaminated air are separated and the most contaminated air can be found above the occupied zone.

The design procedure for displacement ventilation deals with the velocity in front of a wall-mounted diffuser by expressing the distance from the diffuser to an area where the velocity has decreased to 0.2 m/s (in many cases measured 0.1 m above the floor). The research described in this article is focused on the flow from wall-mounted low velocity air terminal devices. It is the aim of this work to obtain results which can simplify and improve the practical design procedure.

- It is important to examine the flow in front of an air terminal device and to investigate if this flow can be treated unconnected with parameters as room geometry (generally speaking), heat source location and location of exhaust opening, etc. The design procedure is simplified if the flow depends only on some main parameters as e.g. type of diffuser, obstacles on the floor, flow rate and Archimedes number of the flow. It is especially a simplification if the influence of width and length of the horizontal section is insignificant. The expectation of this simplification is indicated in figure 1 by the dotted line. An equivalent situation is known in mixing ventilation where the flow from air terminal devices can be described relatively independent of the recirculating flow in the room.

- Furthermore, it is important to obtain a quantitative description of the flow along the floor. The flow along the floor in a room with buoyancy driven ventilation is the only air movement which influences the occupants'comfort. A description of this air movement will therefore make it possible to obtain a detailed picture of the thermal comfort of the room which is a valuable information compared with the knowledge of distance to the 0.2 m's velocity level.

- One of the main problems in connection with computational fluid dynamics used for the prediction of room air movement is to obtain a practical description of the boundary conditions at the supply opening. Experimental work on the flow from diffusers may give important information which can be used for the individual description of different supply openings.

WALL-MOUNTED LOW VELOCITY DIFFUSER

Figure 2 shows the wall-mounted low velocity diffusers which are tested and discussed in this article. The diffusers are of different designs and they cover flow rates of 50 - 300 m^3/h, except diffuser type F which is designed for a flow rate of 500 - 1400 m^3/h.

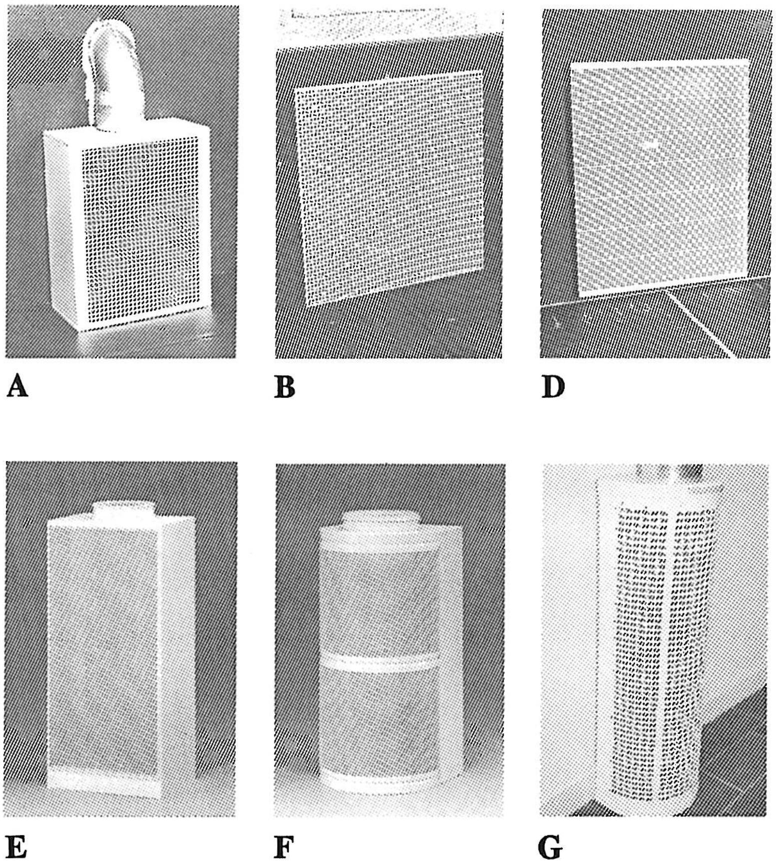

Figure 2. Six different wall-mounted low velocity diffusers for displacement ventilation.

Diffuser type A has a supply velocity profile which is very constant over the entire supply area, while diffuser type B has a supply velocity with a large variation over the supply area both in speed and in direction, see reference [1].

Diffuser type D can be adjusted to two different modes. It can either work as a traditional diffuser, D_1, or it can work with an internal induction unit, D_2, which increases the flow rate at the diffuser surface with a factor of 2.5 compared with the supply flow q_o. The supply temperature T_o will be increased accordingly. The diffuser with the induction unit is especially used for displacement ventilation in systems generally designed for mixing ventilation (low flow rate and high temperature difference). The diffuser generates a semi-radial flow at the supply surface.

Diffuser type E is a conventional diffuser for displacement ventilation without any devices for the generation of radial flow at the supply surface.

The experiments with diffuser F are mainly made to test the influence of the diffuser size. The diffuser is designed for a flow q_o of 500 - 1400 m^3/h, but it is tested in the range of 100 - 200 m^3/h. The flow from the diffuser is radial.

Diffuser type G generates a radial flow at the supply surface. The velocity distribution is varying over the surface from 70% to 140%. The diffuser is selected for the displacement flow experiments in the International Energy Agency Annex 20 work.

The flow from the diffusers is either given by the flow rate q_o or by a face velocity u_f calculated from

$$u_f = \frac{q_o}{a_f} \tag{1}$$

where a_f is the surface area of the perforated part of the diffuser. u_f is easy to calculate but it is different from the supply velocity measured in the openings of the diffuser. (It is very time-consuming to find the supply velocity u_o based on measurements in a number of openings in the diffuser).

The height h of the different diffusers is an important parameter because the cold flow is influenced by vertical acceleration due to gravity. The height and the area of the diffuser are given in table 1.

Diffuser	A	B	D_1	E	F	G
a_f(m^2)	0.159	0.306	0.437	0.267	1.293	0.188
h(m)	0.48	0.58	0.73	1.00	1.42	0.56

Table 1. Area a_f and height h of the six different low velocity diffusers.

The Archimedes number Ar for a flow is given by

$$Ar = \frac{\beta g h (T_{oc} - T_o)}{u_f^2} \tag{2}$$

where β, g and $(T_{oc} - T_o)$ are volume expansion coefficient, gravitational acceleration and temperature difference between the temperature at a height of 1.1 m and the supply temperature, respectively.

FLOW FROM A WALL-MOUNTED DIFFUSER

The flow from three different wall-mounted diffusers is shown in figure 3. The maximum velocity u_x close to the floor is given as a function of the distance x to the diffuser.

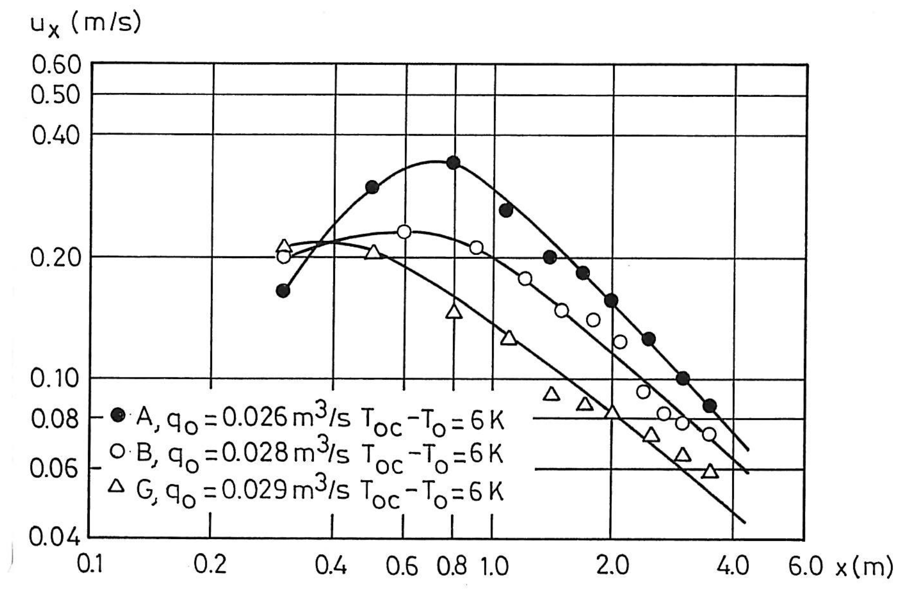

Figure 3. Maximum velocity close to the floor versus distance *x*.

The cold air from supply opening A has a high initial acceleration due to buoyancy effect and a velocity of 0.34 m/s is obtained at a distance of 0.8 m from the diffuser. Type B has a larger diffusion of the supply flow and the gravity will only increase the velocity to 0.23 m/s. The diffuser type G shows an even lower velocity level although the flow to the room is almost the same in all three situations.

Figure 3 indicates that the maximum velocity in the symmetry plane is proportional to $1/x^n$ where the exponent n is close to 1.0 as pointed out by Nielsen et al. [2]. It is also obvious from figure 3 that different diffuser designs generate a different velocity level at the same flow rate and heat load.

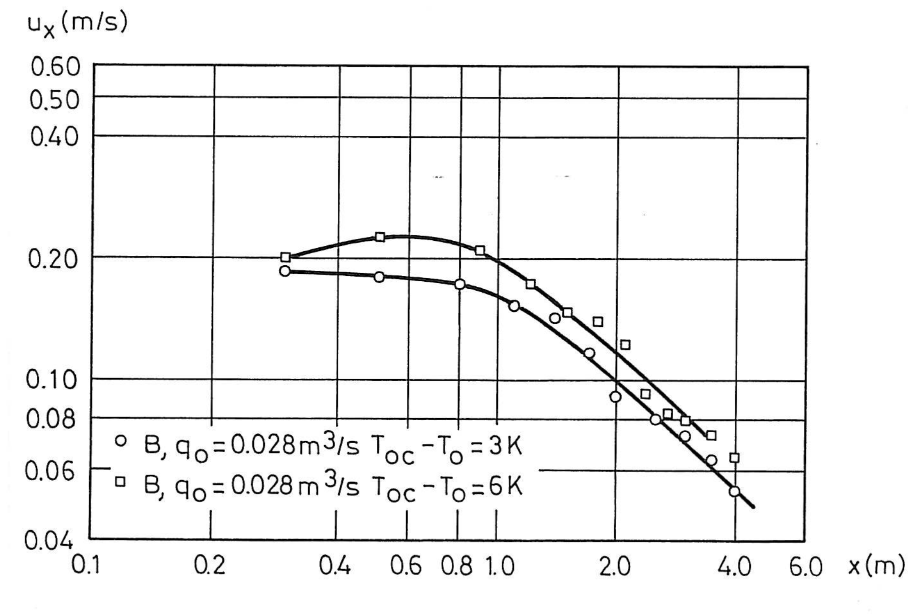

Figure 4. Velocity decay along the floor at different Archimedes numbers. Reference [3].

The velocity at the floor is not only influenced by the flow rate to the room and the type of diffuser. Figure 4 shows that the Archimedes number is an important parameter. A 3°C increase in temperature difference will, for example, increase the velocity from 0.10 m/s to 0.12 m/s at a distance of 2 m from the diffuser. The figure shows that the gravity accelerates the flow close to the diffuser and gives a high initial velocity level at large Archimedes numbers. This effect is very important for the flow in rooms with displacement ventilation and the outcome can be surprising. The velocity level in a room may for example be uninfluenced, although the flow rate is reduced because the heat load in the room requires a reduction of the supply temperature and consequently an increase in the relative velocity level u_x / u_f, see reference [3].

Velocity measurements show that the flow in the vicinity of the floor can be characterized by a normalized velocity profile identical to the universal profile used for the description of wall jet flow, see references [4, 5]. The length scale δ in this profile is defined as the distance from the floor to the height where the velocity has a level which is half of the maximum velocity close to the floor, $u_x / 2$. The profile is given by the universal function $u/u_x = f(\eta)$ where $\eta = y/\delta$, see Rajaratnam [6].

Figure 5 shows the development in δ for three different Archimedes numbers. It can be seen that the height of the flow region is much smaller than the height of the diffuser, even at a distance of 0.5 m from the diffuser. The cold air from the diffuser accelerates towards the floor due to gravity and it behaves like a stratified flow in its further progress along the floor. δ is rather constant while it is proportional to x in a wall jet as indicated by the dotted line in figure 5. The length scale or thickness δ is slightly decreased at increasing Archimedes number.

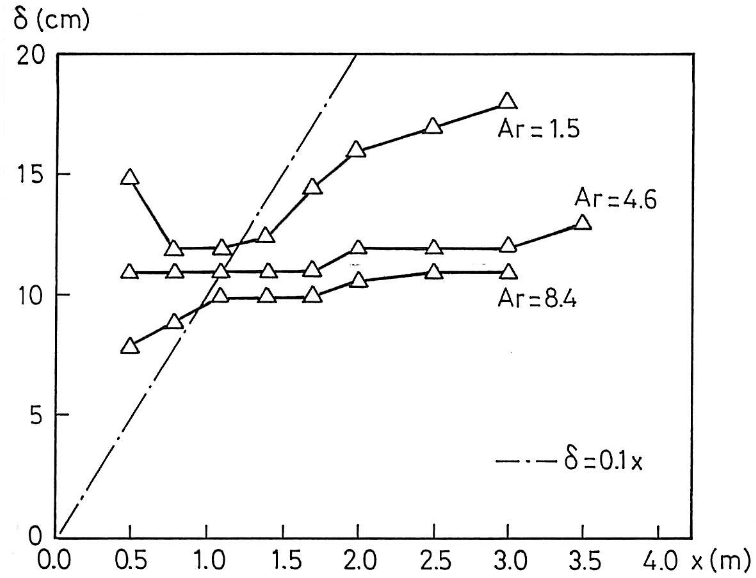

Figure 5. Length scale δ in the flow versus distance from the diffuser. Diffuser type G.

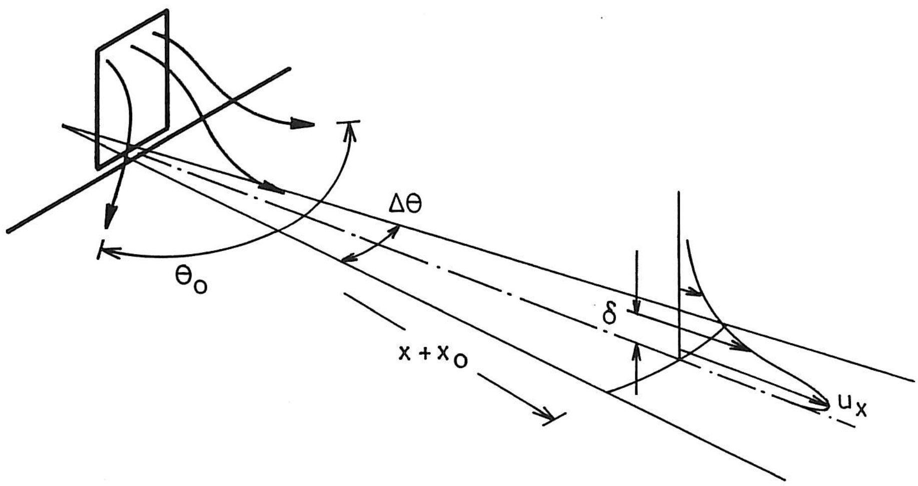

Figure 6. Stratified flow from a wall-mounted diffuser.

The entrainment of air into the flow, or the turbulent mixing process, is diminishing when a vertical temperature gradient is present because the gravity will work against upward movement of heavy fluid and downward movement of light fluid. This is shown in hydraulics by for example Turner [7] and for displacement ventilation by Jacobsen and Nielsen [5].

In the following sections we will develop an equation for the stratified flow in front of a wall-mounted diffuser.

It is known from measurements that the flow is radial and figure 6 shows a small section $\Delta\theta$ of this flow which has a virtual origin located at a distance of x_o from the diffuser. The flow $q_{\Delta\theta}$ within the section $\Delta\theta$ is given by

$$q_{\Delta\theta} = \Delta\theta(x + x_o)\int_o^\infty u\,dy \tag{3}$$

where $\Delta\theta(x + x_o)$ is the width of the section and u is the velocity at the height y. The velocity profile can be given by the normalized profile $f(\eta)$

$$q_{\Delta\theta} = \Delta\theta(x + x_o)\delta u_x \int_o^\infty f(\eta)d\eta \tag{4}$$

It is assumed that the flow is fully stratified which means that δ is constant and that the entrainment is diminishing. $q_{\Delta\theta}$ will be constant and independent of the distance $x + x_o$.

The flow rate $q_{\Delta\theta}$ will be proportional to q_o and $\Delta\theta/\theta_o$, where θ_o is the angular width of the radial spreading close to the diffuser, see figure 6. The flow will obtain this radial spreading partly due to the gravity effect and partly due to the construction of the diffuser

$$q_{\Delta\theta} = \frac{\Delta\theta}{\theta_o} q_o e b_m \tag{5}$$

e is a factor which represents the initial increase in flow rate due to entrainment in the accelerating flow close to the opening and b_m is a factor which adjusts the flow in the direction $\theta = 0$ to the flow profile generated by the diffuser. e and b_m may both be a function of the Archimedes number.

Equations (4) and (5) can be written as

$$\frac{u_x}{q_o} = K \frac{1}{x + x_o} \tag{6}$$

where

$$K = \frac{e b_m}{\theta_o \delta \int_o^\infty f(\eta) d\eta} \tag{7}$$

K is independent of the distance $x + x_o$, but it is a function of the Archimedes number as well as an individual function for different types of air terminal devices. Both x and u_x are assumed to be located in the symmetry plane of the flow.

The development of equation (6) assumes a high Archimedes number, but the structure is also valid for cases where the Archimedes number is very small. In this case the flow will be a part of a potential core or a part of a three-dimensional or radial wall jet. The velocity will in most cases be proportional to $1/(x + x_o)$ and equation (6) will therefore be able to predict the velocity u_x when the K-value is adjusted to the situation, see reference [3].

It is possible to obtain a normalized version of the equation for a more general description of the flow. The velocity u_x is normalized by the face velocity u_f and the length x by the height of the diffuser h

$$\frac{u_x}{u_f} = K_{dr} \frac{h}{x + x_o} \tag{8}$$

where

$$K_{dr} = \frac{a_f e b_m}{h \theta_o \delta \int_o^\infty f(\eta) d\eta} \tag{9}$$

The variables in equation (6) and (8) are easy to measure for a given diffuser and the equations are therefore simple to use in a practical design procedure.

Velocity distribution in rooms with displacement ventilation is also discussed by Mathisen [4], Sandberg and Holmberg [8] and by Sandberg and Mattsson [9].

VIRTUAL ORIGIN OF THE FLOW

Some of the tested diffusers discussed in this paper generate a velocity decay of $1/x^n$ where n is slightly different from 1.0. Figure 7 shows an example where the measurements are in agreement with equation (6) for $x > 2.0$ m, while the equation overestimates the velocity closer to the diffuser.

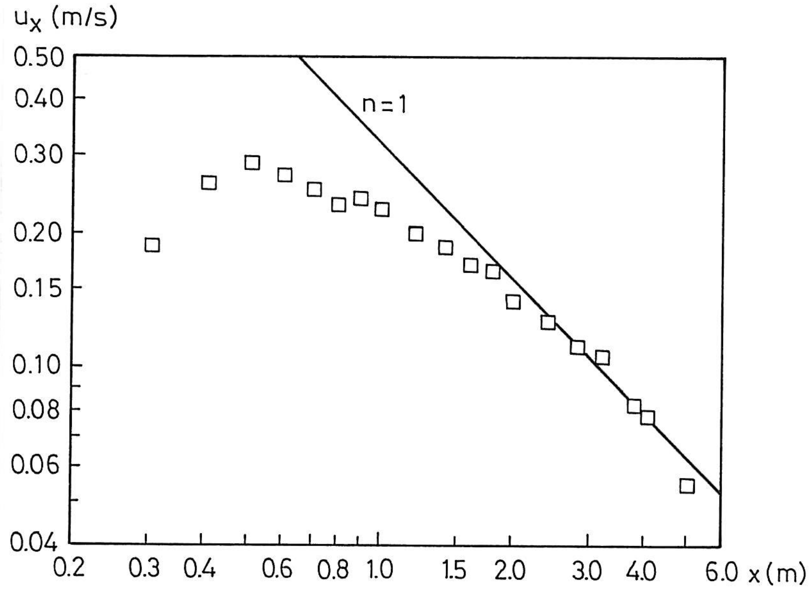

Figure 7. Velocity decay in the flow from a wall-mounted air terminal device type D_1. $q_o = 0.028\ m^3/s$ and $Ar = 45.8$.

The presence of a virtual origin located at some distance x_o behind the diffuser can explain the velocity decay shown in figure 7, but deviations of the same type will also take place if the flow is influenced by entrainment, by non-radial flow or by negative growth in the lenght scale δ. More detailed measurements are therefore necessary to determine if the influence especially is from the presence of a virtual origin located at some distance from the diffuser.

Figure 8 shows the flow direction measured with smoke close to the floor. The conditions for the experiment are close to the conditions in figure 7. It can be seen from the figure that the flow close to the symmetry line has a location of the virtual origin corresponding to $x_o \sim 0.5\ m$, although the measurements are rather scattered. It is also obvious from the figure that the general flow is radial, even rather close to the sidewalls.

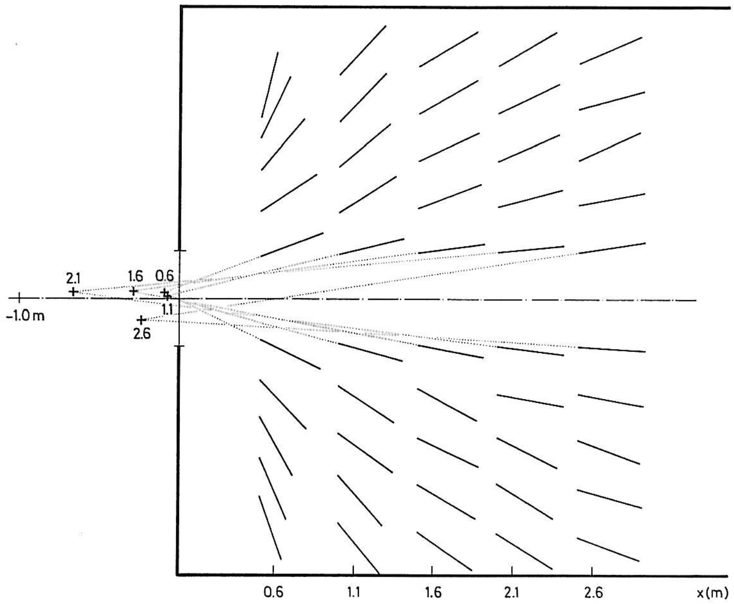

Figure 8. Flow directions at the floor. Diffuser type D_1. $q_o = 0.028\ m^3/s$ and $Ar = 47$.

Figure 9 shows the earlier measured velocity u_x versus $x + x_o$ where $x_o = 0.5$ m. It can be seen that the velocity decay is close to $1/(x + x_o)$ for $x > 1.5$ m which indicates that the measurement of a virtual origin will improve the presentation of the results close to the diffuser. Many measurements show, however, that most of the diffusers have virtual origins which are located very close to the surface of the diffusers which leads to small x_o. The influence of a small x_o is only important close to the diffuser and it is therefore ignored in the presentation in this paper, also because it is very difficult to measure in practice.

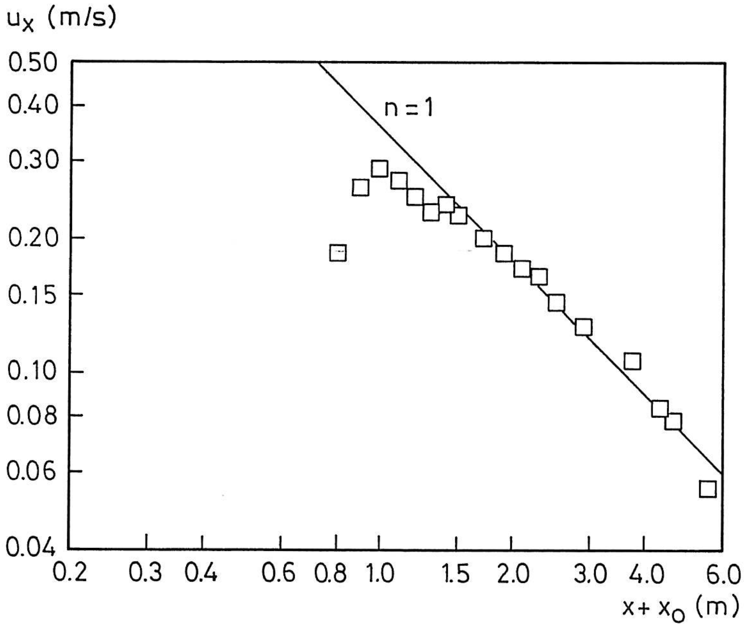

Figure 9. Velocity decay in the flow from diffuser D_1 versus $(x + x_o)$. $q_o = 0.0028\ m^3/s$, $Ar = 45.8$ and $x_o = 0.5\ m$.

MAXIMUM VELOCITY IN THE FLOW CLOSE TO THE FLOOR

Equation (6) gives the velocity distribution along the middle plane of the flow. The equation is easy to use in practice because the variables are the primary variables in a design procedure.

The variable K is a product dependent variable which also is a function of the Archimedes number. A large number of experiments have been made to establish this variable and the results are shown in figure 10. It is obvious that K may be very different for different products as it varies from 5 to 12m^{-1} at high Archimedes numbers.

The figure shows that K increases with increasing Archimedes number. This is due to the fact that gravity will accelerate the vertical flow close to the opening and generate a stratified air movement in a relatively thin layer along the floor where the obtained velocity level will be retained. This effect is also shown in figure 4. Diffuser A shows an increase in velocity at small Archimedes numbers. This increase can be explained by the decrease in radial flow (θ_o) which takes place for the diffuser in this situation.

The high level of K for the diffuser D_2 can be explained by the induction unit used in this product.

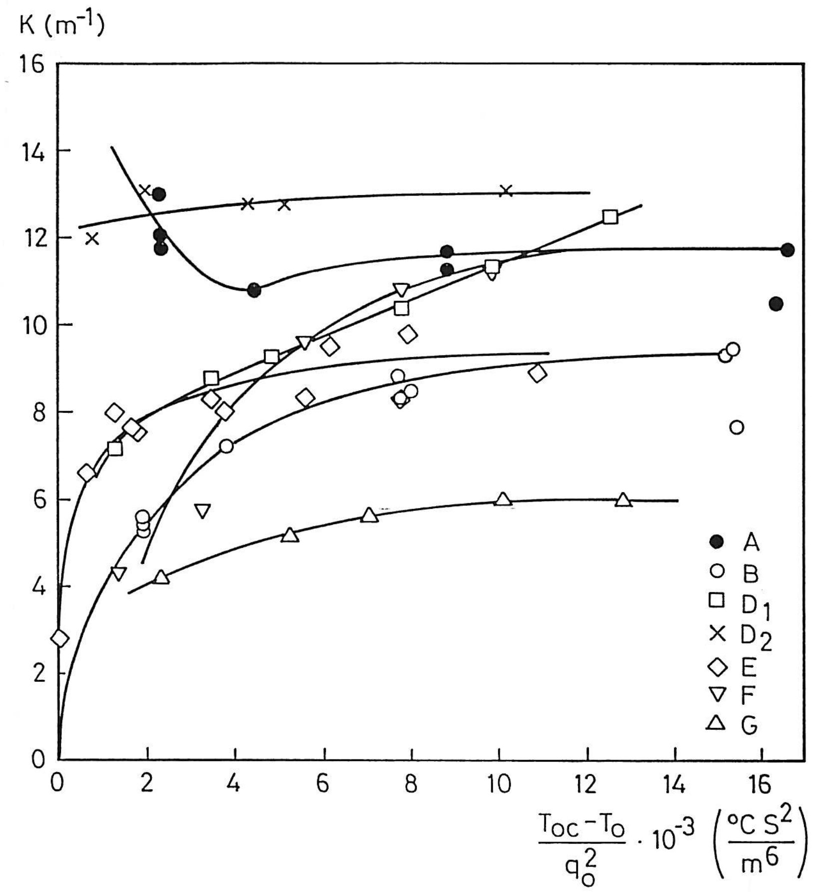

Figure 10. K versus temperature difference and supply flow rate for seven different wall-mounted air terminal devices. x_o = 0.0.

Equation (6) can only be used at som distance from the diffuser as it appears from the figures 3, 4 and 7. This distance is 1.0 m to 1.5 m for most of the diffusers. The diffuser D_2 with an induction unit generates a flow which follows equation (6) for $x > 1.5\ m$ at high Archimedes numbers, while the measurements show that x should be larger than 2 - 3 m for low Archimedes number. Equation (6) will in any case give a velocity equal to or higher than the actual velocity and therefore a value which is suitable for a design procedure.

It is typical that all diffusers, except diffuser F, are designed for rooms with a size comparable to the size of the test room. It might therefore be concluded that the diffusers are tested under conditions and dimensions close to the conditions they are meant to cover in practice and that the velocity level given by the variable K, in figure 10, therefore is typical of a practical application.

Figure 10 shows a large variation in the level of K for the individual products. The influence of different parameters is given in equation (7) and it is possible to make some statements on the design of a diffuser from the influence of the parameters. It is assumed that

$$\int_o^\infty f(\eta)d\eta \sim 1.1 \qquad \delta \sim 0.1\ m \qquad \theta_o = \pi$$

$$e \sim 2.5 \qquad \text{and} \qquad b_m \sim 1$$

which gives a K-value of ~ 7 . Many of the earlier designs of diffusers have a radial distribution of the flow with a relatively high level in the symmetry plane as e.g. a b_m-value of 1.5. This will, in the above-mentioned example, give a K-value of 11, in good agreement with the measurements in figure 10. A further increase in the velocity level will be obtained with a design where θ_o is smaller than π which is also typical of an early diffuser design.

Some new designs will have a lower flow in the direction into the room perpendicular to the wall and a higher flow parallel with the diffuser wall. This can for example be expressed by a b_m-value of ~ 0.85 giving a K-value of ~ 6 . This level is typical of the diffuser type G and this diffuser does in fact have a restricted flow in the direction $\theta = 0$ compared with the flow in other directions.

It is known from stratified flow in hydraulics that obstacles located downstream may influence the length scale δ of the flow, see reference [7]. Most of the measurements are made in test rooms of equal size so it is difficult to determine the influence from the end wall and the sidewalls, but practical experience from the ventilation industry indicates that room dimensions are of minor importance. Measurements in two different rooms with the lengths of 4,2 m and 6,0 m do not show any influence from room dimensions, see reference [12].

Equation (8) is a normalized version of the velocity decay formula. The face velocity u_f and the height of the individual diffuser h are reference values in this equation. Figure 11 and figure 12 show that the dimensionless variable K_{dr} in equation (8) also takes different values for different products. A normalization with the geometrical length scale h does not lead to a continuous description of the K_{dr}-values.

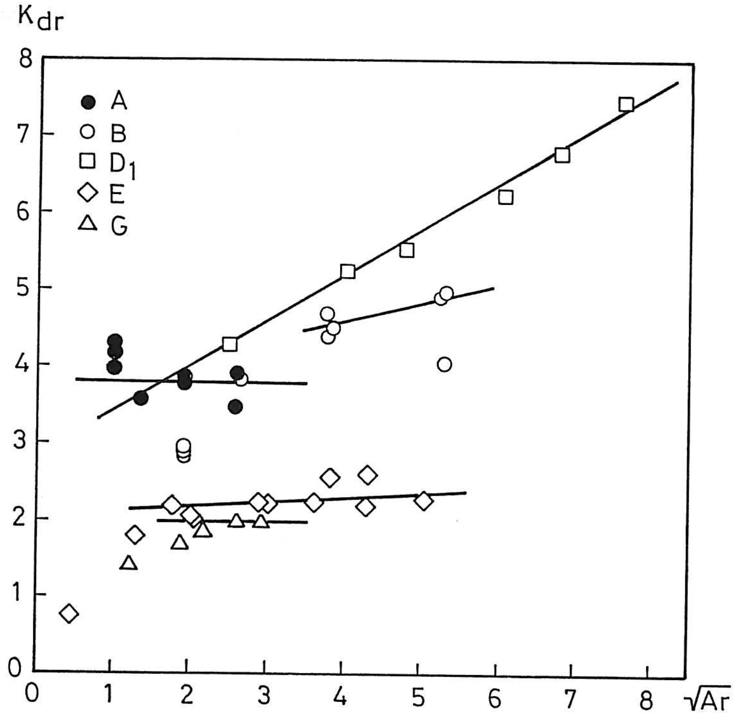

Figure 11. K_{dr} versus Archimedes number for five different wall-mounted air terminal devices. $x_o = 0.0$.

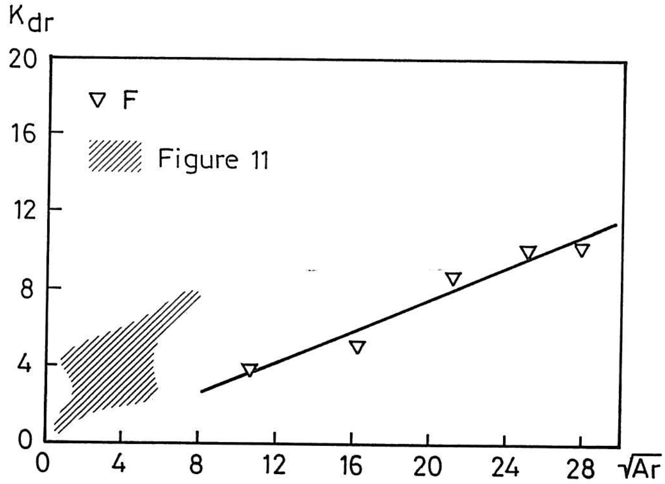

Figure 12. K_{dr} versus Archimedes number for air terminal device type F. $x_o = 0.0$.

Mathisen [4] has shown that the maximum velocity in the flow from a wall-mounted diffuser can be described as a linear function of $\sqrt{Ar}$. The figures 11 and 12 do confirm this assumption for high Archimedes numbers, but an expected deviation takes place at lower Archimedes numbers where the flow only partly is a stratified flow.

STRATIFIED FLOW THEORY

The theory of stratified flow has been used to describe air movement with an entrainment close to zero and a constant length scale δ. The maximum velocity u_x in the radial flow close to the floor, given by equations (6) and (8), is for example based on such a formulation. The theory can also be used for a more detailed description of the flow which takes account of a variable entrainment coefficient and a variable length scale.

Wilkinson and Wool [10] have shown how the flow entrains fluid with lower density close to the opening in a process similar to the flow in a wall jet. This process will be followed with a roller region and a density jump at a certain distance. The entrainment will disappear in the flow further downstream from the density jump. The flow in the entrainment region is called supercritical flow and the flow in the area with diminishing entrainment (gravity current) is called subcritical flow. It has not been possible to identify all these details in the flow from wall-mounted air terminal devices in displacement ventilation, but the decreasing entrainment coefficient as a function of distance, or a local Archimedes number, is typical of stratified flow in a room.

A local Archimedes number is defined by the expression

$$Ar_x = \frac{\beta g \delta \Delta T_x}{u_x^2} \tag{10}$$

where δ, u_x and $\Delta T_x = (T_{oc} - T_x)$ all are local reference values. T_x is the minimum temperature in the flow and it is located close to the maximum velocity u_x. The following expression can be used for an estimate of ΔT_x in case of high entrainment

$$\frac{T_{oc} - T_x}{T_{oc} - T_o} \sim \frac{u_x}{u_f} \tag{11}$$

and it is assumed that temperature variations due to thermal radiation from ceiling to floor can be included in this equation.

The length scale δ will be proportional to x in the supercritical stage and ΔT_x will be proportional to u_x (equation (11)) and therefore proportional to $1/x$ (equation (6)). u_x^2 is proportional to $1/x^2$. The total effect is that Ar_x is proportional to x^2 in the supercritical stage and it will therefore increase with the distance x, which means that the flow moves towards a gravity current (density jump). It is also possible that the local Archimedes number will increase with the distance x in the subcritical stage due to decreasing velocity.

The entrainment coefficient or the entrainment constant E is defined as the ratio between the velocity of inflow into the turbulent shear layer and the velocity scale of the layer, see Morton, Taylor and Turner [11]

$$E = u_e / u_x \tag{12}$$

where u_e is the vertical entrainment velocity into the stratified flow at distance x.

The determination of the velocity u_e is in practice based on measurement of the increase in volume flow in the stratified layer at the floor.

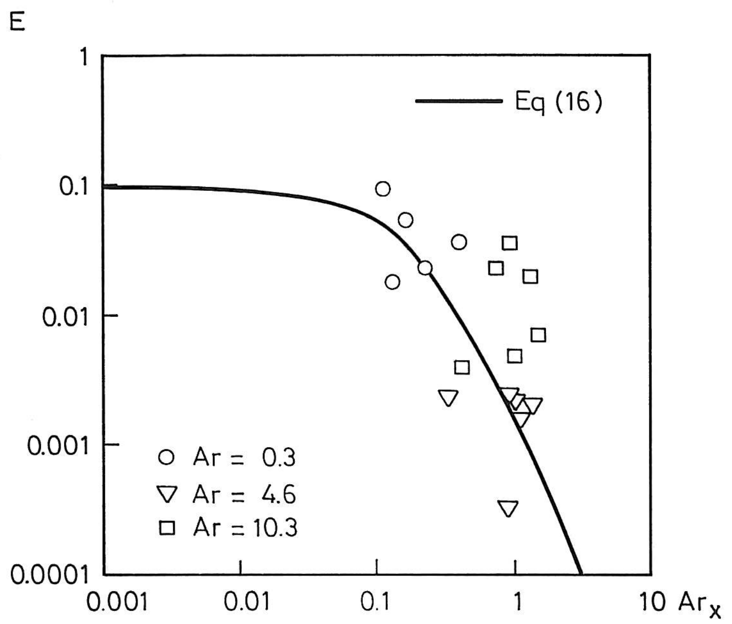

Figure 13. Entrainment coefficient versus local Archimedes number Ar_x for the diffuser type G. Nielsen [12].

The entrainment coefficient is measured at different positions in the flow and at different Archimedes number Ar. Figure 13 shows that the stratified flow moves from a supercritical stage to a subcritical stage with an abrupt decrement of the entrainment coefficient in two of the experiments with high Archimedes number. Figure 13 indicates that transitions from supercritical stage to subcritical stage take place at a local Archimedes number Ar_x which is equal to 1.0.

It is possible to make some statements on the entrainment coefficient from the description in equation (3). The entrainment velocity u_e may be given as

$$u_e = \frac{1}{(x + x_o)\Delta\theta} \frac{dq_{\Delta\theta}}{dx} \tag{13}$$

because the change in flow $dq_{\Delta\theta}$ is equal to the amount of inflow $u_e(x + x_o)\Delta\theta\, dx$.

It is assumed that $(x + x_o)u_x$ is constanct and independent of x at all values of Ar_x as confirmed by the measurements behind equation (6) ($q_o K = (x + x_o) u_x$). $dq_{\Delta\theta}/dx$ is now obtained from equation (4).

$$\frac{dq_{\Delta\theta}}{dx} = \Delta\theta(x + x_o)u_x \frac{d\delta}{dx} \int_o^\infty f(\eta)d\eta \tag{14}$$

Equations (12), (13) and (14) give the following expression for the entrainment coefficient

$$E = \frac{d\delta}{dx} \int_o^\infty f(\eta)d\eta \tag{15}$$

It is interesting to compare this equation with the measurements in figure 5. High Archimedes numbers and increasing distance x show a small $d\delta/dx$ corresponding to a small entrainment coefficient in good agreement with figure 13.

The dotted line in figure 5 for a wall jet type of flow corresponds to $d\delta/dx$ equal to 0.1. In this situation equation (15) gives $E \sim 0.1$ which is confirmed by the measurements in the supercritical stage in figure 13. Equation (15) will also give a diminishing entrainment coefficient in the subcritical stage, $d\delta/dx = 0$, as confirmed by the measurements.

A work on turbulent buoyant jets in shallow fluid layers by Jirka [13] shows that the entrainment coefficient can be given by the following equation

$$E = E_o\left(1 - \frac{Ar_x}{\sqrt{Ar_x^2 + 0.063}}\right)/(1 + Ar_x) \tag{16}$$

where E_o is the entrainment constant for low Archimedes numbers (~ 0.1). It is implied that the local Archimedes number is identical to the overall Richardson number, see [12]. Figure 13 shows that there is good agreement between measurement on the stratified flow in a room and the description given by equation (16) for buoyant jets in shallow fluid layers.

FLOW BETWEEN OBSTACLES

The flow in the vicinity of the floor may be influenced by furniture and other obstacles in the occupied zone. The maximum velocity in the flow is located rather close to the floor (between 1 to 5 cm above the floor) and a great deal of the air movement will therefore take place in this region. Conventional furniture will only have a small influence on the air movement while obstacles placed direct on the floor will block the flow. An opening between this type of obstacles will work as a new supply opening because the flow in the room is stratified. Figure 14 shows the flow between two obstacles where the cold air is supplied in the left side of the room and the heat sources are located in the right side of the room.

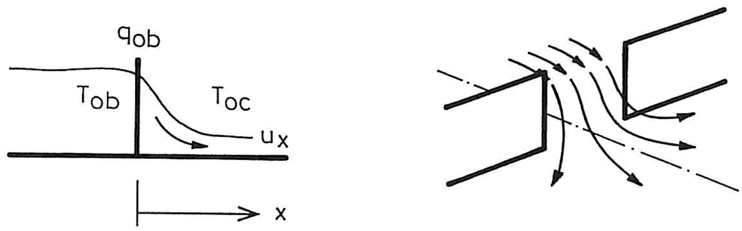

Figure 14. Radial stratified flow between obstacles.

Experiments have shown that the flow from an opening between obstacles can be described as a semi-radial flow like the air movement from a wall-mounted supply opening. The velocity decay can be given by the equation

$$\frac{u_x}{q_{ob}} = K_{ob} \frac{1}{x} \tag{17}$$

u_x is maximum velocity at distance x from the opening and q_{ob} is the excess air supplied to the upstream side. u_x is measured in the symmetry plane.

Figure 15 shows the measurements of K_{ob} in equation (17). The structure of equation (17) and the distribution of K_{ob}-values are equivalent to the structure of equation (6) and the structure of K-values. The temperature difference $T_{oc} - T_{ob}$ is the difference between the temperature measured at a height of 1.1 m in front of the opening and the lowest temperature in the opening between the obstacles.

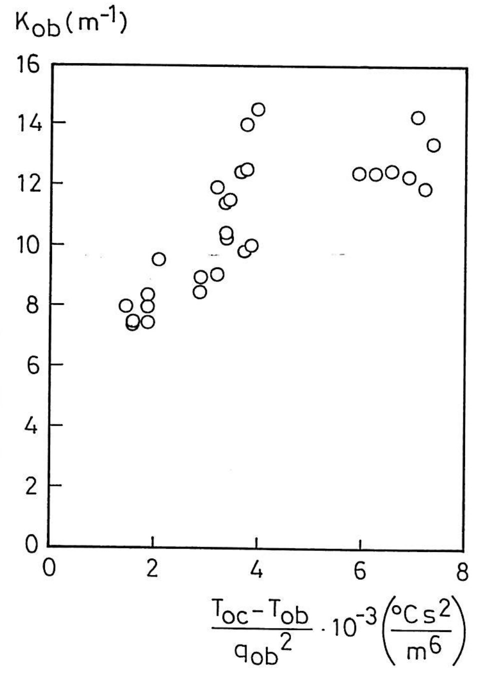

Figure 15. K_{ob} versus flow rate and temperature difference.

It is interesting to see that the level of the variable K_{ob} is only slightly larger than the level of K.

The width of the opening is varying from 0.1 m to 1.5 m in the experiment. Measurements show that the importance of the width is less obvious and results with different widths are given in figure 15.

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CONCLUSIONS

Wall-mounted air terminal devices are often used in displacement ventilation. The flow from an air terminal device will accelerate in a vertical movement close to the opening due to the gravity effect when inlet air is colder than room air. Consequently the airflow will move along the floor in a radial pattern and behave like a stratified flow. The airflow will influence the occupants' thermal comfort and it is therefore important to develop an expression for the flow for design proposals.

Measurements show that the velocity at the floor is not only influenced by the flow rate to the room. It is also influenced by the temperature difference - or by the Archimedes number - and the velocity level may vary for different types of diffusers.

The flow is stratified at large temperature differences. This is indicated by a constant height of the cold flow independent of the distance from the supply opening. It is shown that the radial flow has a virtual origin close to the front of the diffuser. The velocity level in the flow along the floor is inversely proportional to the distance from the diffuser. The velocity decay can be described individually for each type of diffuser by a single equation and a variable which is a function of the Archimedes number. It is further shown that the maximum velocity can be described as a linear function of the square root of the Archimedes number.

Measurements of the entrainment coefficient of the radial flow along the floor show supercritical and subcritical areas of the flow and a semi-empirical theory of stratified flow supports the measurements.

Openings between obstacles placed direct on the floor will generate a flow similar to the air movement in front of a diffuser. It is shown that the velocity distribution can be described with an equation system with the same structure as the system describing the stratified flow from wall-mounted diffusers.

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APPENDIX A

Distribution of volume flow in the radial stratified air movement along the floor

Figure A1 shows the radial distribution of volume flow at a distance from the diffuser where the entrainment factor E is close to zero. The total flow is equivalent to $q_o e$ where e is a factor which represents the initial increase in flow rate on account of entrainment in the vertical - and accelerating - flow close to the opening. It is assumed that the flow will be evenly distributed in all directions within $-\theta_o/2 \leq \theta \leq \theta_o/2$

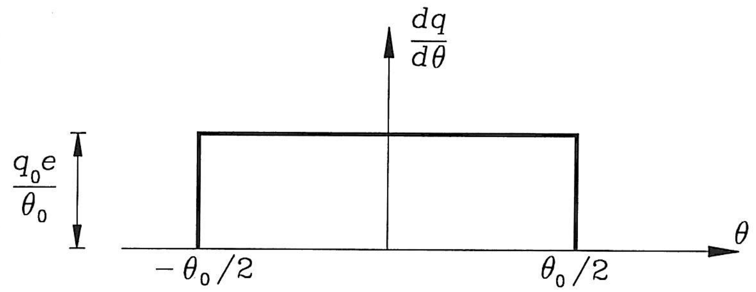

Figure A1. Radial distribution of volume flow.

The total flow is given by

$$\int_{-\theta_o/2}^{\theta_o/2} \frac{dq}{d\theta}\, d\theta = \left[\frac{q_o e}{\theta_o}\right]_{-\theta_o/2}^{\theta_o/2} = q_o e \tag{A1}$$

The flow $q_{\Delta\theta}$ is the flow within the section $\Delta\theta$ and it is equivalent to

$$\frac{q_{\Delta\theta}}{\Delta\theta} = \frac{q_o e}{\theta_o} \tag{A2}$$

Figure A2 shows that the radial distribution of volume flow may be a function of the direction θ. The total flow is in this case given by

$$\int_{-\theta_o/2}^{\theta_o/2} \frac{dq}{d\theta}\, d\theta = \left[\frac{q_o e}{\theta_o}\, b\right]_{-\theta_o/2}^{\theta_o/2} = q_o e \tag{A3}$$

where b is a function of θ.

The flow around the symmetry line is given by

$$\frac{q_{\Delta\theta}}{\Delta\theta} = \frac{q_o e}{\theta_o} b_m \tag{A4}$$

where b_m is a factor which adjusts the flow in the direction $\theta = 0$ to the actual flow profile.

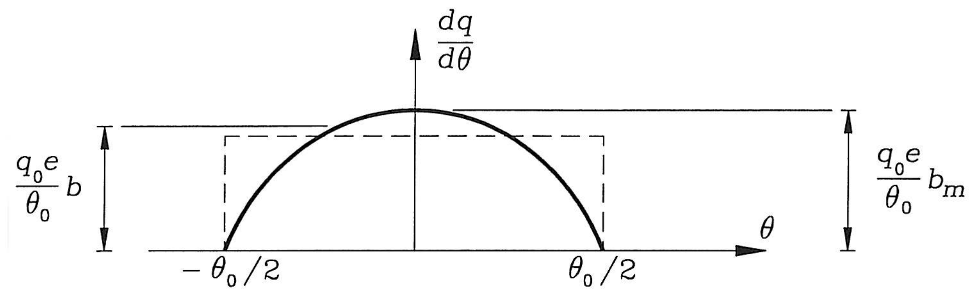

Figure A2. Radial distribution of volume flow with a variable distribution.

The variation in flow in different directions is achieved by a variation of the maximum velocity $u_{r\theta}$ and to some extent also by a variation of the thickness δ_θ in different directions.